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A THEORETICAL ANALYSIS ON THE ENERGY PRODUCTION OF III-V MULTI-JUNCTION SOLAR CELLS UNDER REALISTIC SPECTRAL CONDITIONS

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ABSTRACT: In this paper we present a methodology which uses the detailed balance method to determine the optimum bandgap combination of III-V triple-junction solar cells for the highest yearly energy production. As an example for the methodology we analyse two geographical locations on Earth with distinct spectral conditions. For these places the monthly average of the measured aerosol optical depth and the precipitable water are used to calculate direct solar spectra with a discretisation of one spectrum per hour. The model is used to analyse the spectral sensitivity of the bandgap design of four practical III-V triple-junction solar cell structures. In addition, the impact of the designated operating temperature is investigated. Furthermore, the ideal bandgap combination for a maximal energy harvest is calculated for each location. It is shown that structures optimized for the standard AM1.5d reference spectrum yield nearly optimal energy harvesting efficiencies at geographical locations with “red-rich” spectral conditions. However, the choice of the right bandgap combination is essential. By contrast, structures should be re-optimized for locations with a high share of blue light.

Keywords: Energy Performance, Multi-junction Solar Cell, Modelling

1 INTRODUCTION

III-V multi-junction solar cells are widely used in terrestrial concentrator systems. Their central beneficial feature is that various solar cells with different bandgap energies can be stacked monolithically. However, this approach results in a wide range of possible design configurations concerning the number of stacked pn-junctions, their individual bandgap energies and the respective degree of transparency of each subcell in order to achieve current-matching conditions. Typically these cells are optimized with respect to standard testing conditions. Currently, concentrator solar cells are rated under the AM1.5d ASTM G-173-03 provided by the American Society for Testing and Materials (ASTM) [1] and at cell temperatures of 298 K. However, in real applications the main value of interest is not the efficiency under a reference spectrum but the annual energy production under realistic operating conditions. This includes considering the operating cell temperature, the varying intensities and spectrum changes due to the concentrating optics or during the course of day or year. Since triple-junction solar cells are known to be sensitive to changes in the solar spectrum [2], the spectral variation should be taken into account when calculating the annual energy production of these solar cells. The solar spectrum varies due to changes in air mass and atmospheric composition. In particular aerosol optical depth and precipitable water are known to have a significant impact on the solar spectrum [3,4]. Thus, for triple-junction solar cells the question arises to what extent the optimal solar cell configurations differ if optimized on the highest efficiency or on the annual energy production for different places on Earth.

In order to reduce the number of time-consuming and expensive experiments it is imperative to carry out theoretical investigations on the performance of different design configurations of III-V multi-junction solar cells. Most of the work done in this field so far is focused on achieving high efficiencies under a particular reference spectrum. A good overview of the different approaches for calculating theoretical efficiencies of multi-junction solar cells was presented by Kurtz et al. [5]. Yet, we found that the choice of the reference spectrum can even have a stronger impact on the energy production than adding additional junctions [6]. This indicates that the usual optimization approach does not necessarily yield the best results when looking at the energy production in real applications. The topic of the influence of spectral variations on the performance of multi-junction solar cells has found increasing attention by several research groups, e.g. [7,8,9]. Due to the growing number of concentrator PV systems based on III-V multi-junction solar cells in the market, methods for predicting the expected yearly energy production of these systems have become quite urgent.

In this paper a theoretical analysis is carried out using a model which is based on the detailed balance method first introduced by Shockley and Queisser [10]. Two different places on Earth are analyzed, for which we derived sets of hourly spectra for a period of a whole year based on measured spectral data. We analyze the bandgap combination of four triple-junction solar cell concepts. It is investigated how strongly the optimal design depends on the intended place of operation. Finally the performance losses due to spectral variations are discussed.

2 MODELLING APPROACH

2.1 Model description

The generation and recombination current of the investigated triple-junction solar cells are calculated with the program “etaOpt” which has been developed at the Fraunhofer Institute for Solar Energy Systems ISE and is available for download [11,12]. The underlying model is based on the detailed balance method first introduced by Shockley and Queisser [10], i.e. only radiative recombination is considered. The generation current is computed under the assumption that all subcells have an external quantum efficiency (EQE) equal to one. In order to improve current matching under a certain spectrum photocurrent from upper subcells can be transferred to lower ones. In reality this is achieved by thinning the absorbing layers. In order to model this effect each subcell has an individual degree of transparency, which can be adjusted to improve current-matching. The current-voltage characteristic of the cell is then modelled with the one-diode model.

2.2 Spectra

Spectra for two geographical locations on Earth are computed. The spectra are simulated with the computer code SMARTS 2.9.5 [13,14,15]. For this purpose realistic atmosphere data is used. In particular monthly average data based on long term measurements of the aerosol optical depth and the precipitable water from the AERONET database is used [16]. For every location direct solar spectra are calculated taking into account the varying air mass. The aerosol optical depth at 500 nm and the precipitable water are varied for each month. The remaining atmospheric inputs are left constant. In order to keep the computing time within a tolerable limit, we model each day with a discretisation of one spectrum per hour. For the rating of different designs under standard testing conditions we use the standard reference spectrum for direct normal spectral irradiance AM1.5d ASTM G-173-03 provided by the American Society for Testing and Materials (ASTM) [1].

2.3 Scenarios

Our choice for the locations on Earth is based on two criteria: First, we require a solid data base for the atmosphere data, which is based on at least five years of measurement. Second, we choose locations, which are strongly distinct in their atmospheric conditions. Based on these criteria, we chose the two locations Solar Village, Saudi Arabia and La Parguera, Puerto Rico. For the desert location of Solar Village the SMARTS desert aerosol model and a subtropical atmosphere are used, whereas the maritime model and a tropical atmosphere are applied for La Parguera. The remaining inputs (besides air mass, aerosol optical depth and precipitable water) are set equal for both locations, using the values recommended by SMARTS.

For each location more than 4000 single spectra are calculated, which are used for the energy harvesting calculations in Section 3.3. In order to get an impression of the spectral conditions at an individual location it is useful to take a look at the yearly average spectrum, which is calculated as the average of the single spectra. Figure 1 shows a comparison of the reference spectrum and the yearly average spectra at Solar Village and La Parguera. Solar Village is a desert location and typically shows a relatively high aerosol optical depth at 500 nm (0.32 in average). Thus the incident light has a relatively low share of blue light – the average spectrum of this location is thus rather “red-rich”. In contrast the spectral conditions in the Caribbean are characterized by a relatively low aerosol optical depth (0.15 in average). Consequently, the yearly average spectrum at La Parguera is characterized by a much higher blue share and a lower amount of infrared light. In addition, it is noteworthy that La Parguera has a rather high amount of precipitable water in average. This becomes obvious when comparing the water absorption bands for the spectra shown in Figure 1.

Concerning the operating conditions we assume a concentration factor of 500 suns, which represents a reasonable design average for today’s concentrator systems. The dependence of the cell temperature in concentrator systems on the operating conditions (e.g. ambient temperature and spectral conditions) is still discussed intensively in the scientific community. In this paper we assume a constant cell temperature of 338 K. From our experiences this value represents a reasonable average, which is also used by other groups [9].

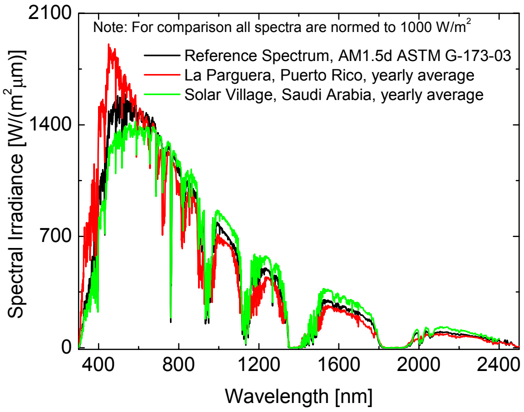

Figure 1: Comparison of the reference spectrum AM1.5d ASTM G-173-03 and the yearly average spectra at Solar Village in Saudi Arabia and La Parguera in Puerto Rico.

3 RESULTS AND DISCUSSION

The energy production of four already realised triple-junction solar cell concepts is investigated. All concepts reached efficiencies of over 40% under the concentrated AM1.5d spectrum:

- **LM**: Lattice-matched $Ga_{0.50}In_{0.50}P$/ $Ga_{0.99}In_{0.01}As$/Ge (1.87, 1.41 and 0.66 eV) [17,18,19].
- **MM**: Metamorphic $Ga_{0.35}In_{0.65}P$ and $Ga_{0.83}In_{0.17}As$ grown on Ge with a lattice-mismatch of 1.2% (1.67, 1.18 and 0.66 eV) [20].
- **IM1**: Inversely grown $Ga_{0.5}In_{0.5}P$ and GaAs top junctions with a $In_{0.27}Ga_{0.73}As$ bottom cell (1.84, 1.41 and 1.00 eV) [21].
- **IM2**: Inversely grown $Ga_{0.51}In_{0.49}P$ and $In_{0.04}Ga_{0.96}As$ top junctions with a $In_{0.37}Ga_{0.63}As$ bottom cell (1.83, 1.34 and 0.89 eV) [21].

3.1 Optimization for the reference spectrum

As described in the introduction multi-junction solar cells are usually optimized and rated for a particular reference spectrum and standard testing conditions, which typically include a cell temperature of 298 K. Following this approach we first optimize the ideal efficiencies for the analyzed bandgap combinations under the reference spectrum AM1.5d ASTM G-173-03 and a concentration ratio of 500 suns. Figure 2 shows the simulated efficiencies and the optimal subcell transparencies for the four designs calculated with our theoretical model assuming a cell temperature of 298 K. In addition, the optimal triple-junction bandgap combination of 1.74/1.17/0.69 eV is shown leading to an efficiency of 61%.

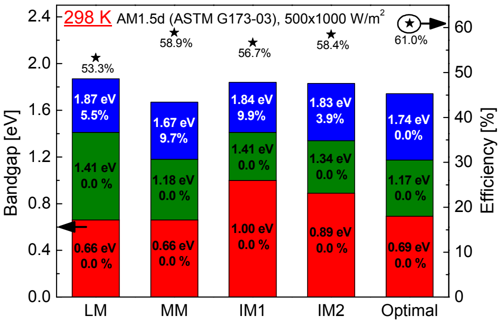

Figure 2: Bandgap combinations of four triple-junction solar cell concepts, which have already been realized with champion efficiencies. The stars in the graph mark the simulated ideal efficiencies of these bandgap combinations under the reference spectrum AM1.5d ASTM G-173-03 with a concentration ratio of 500 suns and a cell temperature of 298 K. The rightmost bar marks the optimal bandgaps for these conditions. Furthermore, the optimal subcell transparencies and the bandgap energies are indicated for each subcell.

The approaches "MM" and "IM2" have high theoretical efficiencies of 58.9% and 58.4%, respectively, whereas the "IM1" as well as the lattice-matched approach "LM" show lower performances of 56.7% and 53.3%, respectively. In the optimal configuration of all four concepts current is required to be transmitted from the top cell to the middle cell, whereas the middle cell absorbs all light. Obviously, the optimal transparency of the bottom cell is always zero as higher values would imply loosing current.

3.2 Optimization for elevated operating temperature

In real concentrator applications the solar cells usually operate at temperatures higher than 298 K. Thus, it might be useful to optimize the solar cell structures for higher operating temperatures. Figure 3 shows the calculated ideal efficiencies under the same spectral conditions as in Figure 2 but for a cell temperature of 338 K. The bandgaps of the four triple-junction concepts decrease slightly according to the temperature-dependent bandgap models in Ref. [22,23].

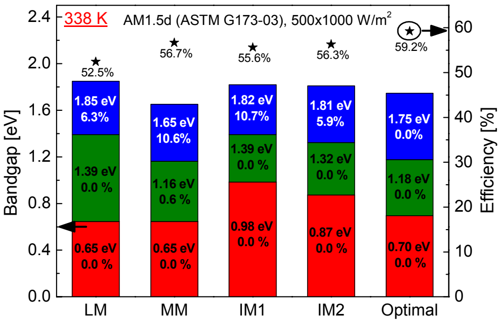

Figure 3: Ideal efficiencies under similar spectral conditions as in Figure 2 but for a cell temperature of 338 K. The bandgaps of the four triple-junction concepts were adjusted according to the temperature dependencies given by Levinshtein et al. [22,23].

As the decrease in bandgap energy with rising temperature is stronger for higher bandgap materials the top cells can be thinner leading to slightly higher optimal top cell transparencies compared to the optimisation for 298 K. For perfect current-matching of the metamorphic approach "MM" the middle cell needs to have a transparency of 0.6%. All maximum efficiencies are lower for the high temperature scenario due to the decreasing voltage with higher temperatures. In order to reduce this effect the optimal bandgap combination for a temperature of 338 K has slightly higher bandgaps than for 298 K.

3.3 Optimization for maximal energy production

The optimization above results in ten different solar cell designs characterized by their bandgap energies and subcell transparencies. In the following the energy yield at Solar Village and La Parguera is investigated. As described in Section 2.2 and 2.3 we model each day with a discretisation of one spectrum per hour. Thus, a spectrum was computed for each (daytime-) hour of the year resulting in more than 4000 spectra. Based on these spectra the annual sum of the produced energy, which is computed from the produced energy for each hour in the year, is calculated and is then referred to the irradiated energy. Please note that the hourly irradiated intensity is calculated by integrating the simulated spectra. These are calculated for wavelengths up to 2500 nm. This leads to over-all annual incident energies of 2603 kWh/m^2/a at Solar Village and 4198 kWh/m^2/a at La Parguera. The ratio of the energy produced to the irradiated energy defines the energy harvesting efficiency.

Figure 4 shows the energy harvesting efficiency at Solar Village. The orange and green bars correspond to the designs optimized for the AM1.5d ASTM G-173-03 spectrum with a concentration ratio of 500 suns at 298 K and 338 K, respectively. All five high temperature designs show a slightly lower efficiency than the low temperature designs. This is remarkable since a cell temperature of 338 K is assumed for the calculation of the annual energy production.

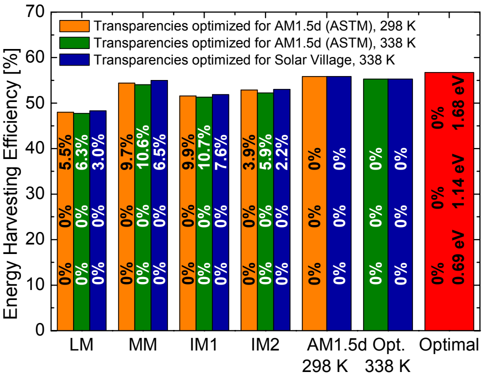

Figure 4: Energy harvesting efficiency at Solar Village, Saudi Arabia for four triple-junction solar cell concepts and the optimal bandgap combinations with degrees of transparency as shown in Figures 2 and 3. The blue bars mark the highest values that can be realized through an optimization of the transparencies for the highest energy yield at Solar Village. The rightmost bar represents the ideal bandgap combination for Solar Village.

The effect is explained by the relative low blue share in the incident light at Solar Village as indicated by the yearly average spectrum in Figure 1. Compared to the reference spectrum the top cells get less light and thus limit the current of the triple-junction structure. As the high temperature designs have higher top cell transparencies their top cell currents are even lower. The same explanation applies for the optimal bandgap configuration as the high temperature design has higher bandgaps than its low temperature equivalent.

A simple design optimization step would be to adapt the subcell thicknesses and thus the transparencies for the intended geographical location. The blue bars in Figure 4 represent the resulting optimal transparencies for each design. Lower top cell transparencies are favourable for all designs due to the low blue share of the incident light at Solar Village. A further step would be to optimize the bandgaps. The rightmost bar shows the optimal design configuration concerning bandgaps and transparencies. Relatively low bandgaps –close to those of the approach “MM” – are optimal due to the “red-rich” incident light.

The comparison of the different designs shows that the metamorphic approach “MM” outperforms the other designs under the spectral conditions found at Solar Village. This is due to the relatively low top cell bandgap of the MM approach, which allows for a high current under the red-rich spectral conditions at Solar Village. In contrast the LM approach shows the lowest energy harvesting efficiency due to its high top cell bandgap. In total, it can be concluded that neither the adaption of the transparencies of the four designs nor the use of novel bandgap combinations leads to a strong improvement in energy yield at the Solar Village location compared to already existing designs.

The energy harvesting efficiency at La Parguera (Figure 5) shows different trends. Due to the high blue share of the incident light the upper cells produce higher currents than under the reference spectrum or under Solar Village spectral conditions.

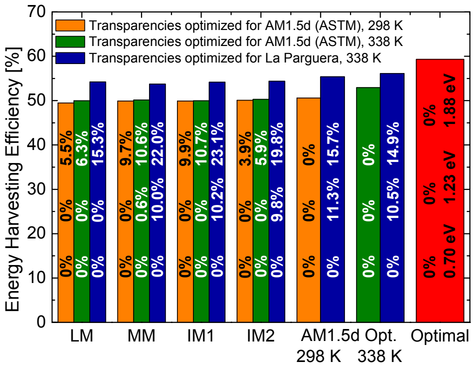

Figure 5: Energy harvesting efficiency at La Parguera, Puerto Rico for four triple-junction solar cell concepts and the optimal bandgap combinations with degrees of transparency as shown in Figures 2 and 3. The blue bars mark the highest values that can be realized through an optimization of the transparencies. The rightmost bar represents the ideal bandgap combination for La Parguera.

Therefore, high top cell and high middle cell transparencies - except for the LM approach - are favourable and lead to strong improvements of the energy harvesting efficiency for all four concepts as well as for the optimal bandgap combinations under the reference spectrum. Thus, the top and middle cell bandgaps are too low. Consequently, the optimal bandgap combination for La Parguera has a high top cell bandgap and leads to a strong increase in energy harvesting efficiency.

It is noteworthy that all four triple-junction concepts as well as the optimal bandgap combinations for the reference spectrum yield approximately the same energy harvesting efficiency. This is explained with the balancing of current and voltage influences. The concepts “LM”, “IM1”, “IM2” and the AM1.5d optimal bandgap combinations have relatively high bandgaps leading to high voltages but lower currents compared to the “MM” approach, which has a lower voltage but very high currents.

It is interesting to evaluate the difference between the efficiency under a reference spectrum and the energy harvesting efficiency as this gives an idea of the losses due to the changing spectra in real applications. In order to exclude temperature effects we compare the efficiencies of the high-temperature (338 K) designs. Figure 6 shows the corresponding ratio of the energy harvesting efficiencies and the efficiency under the AM1.5d ASTM G-173-03 reference spectrum, which is called the energy performance ratio.

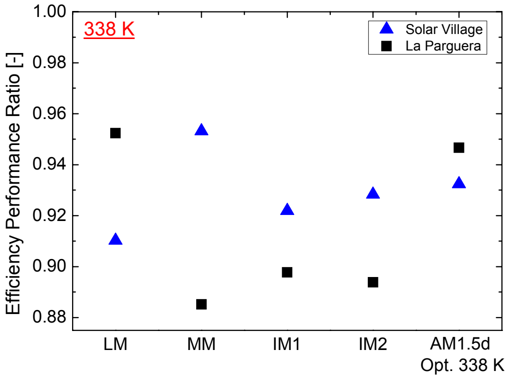

Figure 6: Ratio between energy harvesting efficiency and the efficiency under AM1.5d ASTM G-173-03 with a concentration ratio of 500 suns and a cell temperature of 338 K. The structures correspond to the high-temperature designs shown in Figure 3.

It is found that 88% to 96% of the performance predicted from the rated triple-junction efficiency can be harvested in field. Consequently energy harvesting losses of only 4% can be expected when a triple-junction solar cell operates in a location with advantageous spectral conditions (e.g. MM cells in desert locations, or LM cells in “blue-rich” locations). However, harvesting losses can be up to 12% when the solar cells are not fitting well to the spectral conditions found at the location of operation (e.g. MM, IM1 and IM2 cells at “blue-rich” locations).

4 CONCLUSION

The comparison of the results at Solar Village and La Parguera shows that the usual structure optimization for the reference spectrum AM1.5d does not necessarily provide a good prediction for the optimal structure concerning the energy yield. For locations with “red-rich” spectral conditions (e.g. desert locations) the AM1.5d ASTM G-173-03 optimized structures need to be adopted to absorb more light in the top cell. In contrary for blue-rich spectral conditions the structures should be optimized to have a higher transmission for the top and even the middle cell. Concerning the bandgap combinations it is found that for red-rich spectral conditions the metamorphic approach “MM” provides nearly optimal energy harvesting efficiencies. The realization of novel bandgap combinations is hence not essential. In contrast, for locations with blue-rich spectral conditions novel triple-junction solar cells with higher bandgaps would be favourable. However, taking into account that the investigated locations are rather extreme in terms of spectral conditions, the currently used reference spectrum for concentrator solar cells represents a reasonable average.

In addition, it was shown that a high temperature optimization under the reference spectrum does not necessarily lead to better solar cell structures in terms of calculated energy production. The spectral impact seems to dominate the influence of different operating temperatures. The changing spectral conditions lead to a loss in efficiency of 4% to 12%rel.

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